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THE ACTION OF MERCURY ON STEEL AT HIGH
PRESSURES.

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UNDER ordinary circumstances steel and mercury are inert with respect to each other, as is shown by the possibility of carrying mercury for indefinite periods of time in steel flasks. But there seems to be a widely spread notion that under higher pressures there may be some action not operative at lower pressures. This possibility is usually ascribed to the extraordinary mobility of the mercury molecule. For instance, every one who has had experience in making joints for pressures of a few atmospheres knows that mercury will easily find its way through holes impervious to water or less viscous fluids. It has therefore been thought probable that under higher pressures the easily moving mercury molecule might be forced through the very pores of the solid metal itself, and that in consequence it might be impossible to hold mercury at all in metal receptacles at high pressures. This view has received its highest confirmation from some often cited experiments of Amagat. Amagat¹ has described how in one case mercury was forced by a pressure of 3000 atmospheres in a fine spray through 8 cm. of cast steel, in which no flaw could be afterward detected with the microscope. Amagat explained this effect in the way suggested above by assuming that the mercury was forced by the high pressure through the very intermolecular pores of the solid steel. It is worthy of notice that it was found possible to avoid this difficulty merely by making another apparatus with thicker steel parts. There is also work by Cailletet and Collardeau² on the vapor pressure of mercury at high temperatures that seems to demand in explanation

¹ Amagat, *Ann. de Chim. et Phys.* (6), **29**, 87-88 (1893); also *Compt. Rend.* March 2, 1885.

² Cailletet, Collardeau and Riviere, *Compt. Rend.* **130**, 1585-1591 (1900).

that the mercury was forced through solid steel by comparatively low pressures at sufficiently high temperatures.

In measurements undertaken by the author of various physical constants at high pressures, this question of the action of mercury and steel became of vital importance. For instance, the methods adopted to measure compressibility assumed that there was no penetration of the mercury into the steel containing vessel, as do also the methods used more recently in determining the variation with pressure of the freezing temperature of mercury and its change of volume on freezing. The preliminary work at low pressures made it seem probable that at least over the pressure range used by Amagat the effect described by him does not really exist in the grades of steel used by him, and that the observed effect was due more likely to flaws in the steel. At the same time it was found that at higher pressures there is undoubtedly an effect important enough to demand the redesigning of the apparatus for the measurement of the change of volume on freezing. It is the purpose of this paper to describe the various experiments made to prove the undoubted existence of the effect, and to offer a qualitative explanation. The effect was run across only incidentally, and it was examined only so much as was necessary for the work in hand. No endeavor has been made to make the experimental investigation or the explanation complete, as this would lead too far afield.

The effect was first found during an attempt to measure the change of volume of mercury on freezing by a method similar in many respects to that of Tammann.³ It was found that cylinders of hardened chrome nickel steel would support very much less internal pressure when this pressure was transmitted by mercury than when the transmitting fluid was some other liquid such as water. The pressure might be less in the ratio of three or four to one; thus cylinders which stood without breaking 24000 atmospheres when the pressure was transmitted to the interior by a mixture of water and glycerine broke on the next application of pressure at 5-8000 atmos. if the transmitting fluid were mercury. These few preliminary experiments under varying conditions made the existence of an effect seem probable, but pointed to nothing conclusively. It might well be that there was a flaw running the entire length of the steel bar from which all these pieces were cut, into which the mercury forced its way in consequence of its greater mobility, in preference to the water, or it might be that there was here a fatigue effect, the steel breaking more readily on the second application of pressure with the mercury because of the exceedingly high pressure to which it had been previously exposed by

³ Tammann, *Kristallisieren und Schmelzen* (1903), p. 204.

the water. This explanation, however, was opposed by all previous experience with this steel. In any event, the effect of the mercury was entirely different from that found by Amagat, as there was never any tendency for the mercury to squirt through the steel, but there was always sudden rupture, the cylinder cracking down one side in a plane containing the axis. To show conclusively that a cylinder of hardened nickel steel will really not stand so much pressure when the transmitting liquid is mercury as when it is some other liquid such as water, the following experiment was undertaken. A bar of this special steel (Krupp Special Chrome Nickel Steel E. F. 60.0) was cut into twelve pieces each $8\frac{1}{2}$ " long and 2" diameter. (See Figure 1.) The pieces were numbered and their orientation in the original bar carefully noted. They were then each pierced with a $\frac{1}{2}$ " hole reamed to size, turned on the outside true with the hole, and hardened by heating to a bright cherry red and quenching in a heavy tempering oil. Every other cylinder (Nos. 1, 3, 5, 7, 9, 11) was filled with mercury and tested by applying pressure to the mercury by means of a piston actuated by a hydraulic press. The test conditions of these different cylinders were varied somewhat by changing the rapidity with which pressure was applied; in other respects the conditions were the same. The other cylinders were tested in a similar way, except that the fluid transmitting the pressure was not mercury; being in four of the six cases water and glycerine, in the others ether and carbon disulphide respectively. The pressure in the test cylinders was determined from the pressure of the fluid actuating the hydraulic ram, multiplying in the ratio of the areas of the two pistons. An unknown error is introduced here by the friction of the packing, but in other experiments with similar cylinders in which the pressure inside the small cylinders was measured directly it was found that the error so introduced was nearly constant and easy to correct for. The correction so found was used in the results to be given. In any event, the correction is less than the irregularities introduced by other causes.

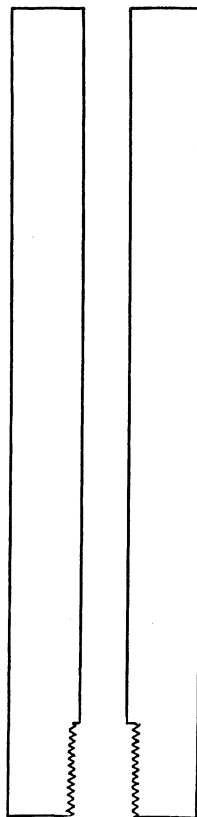


FIGURE 1. Form of the test cylinders broken with mercury.

The accompanying table (see Table I) shows the results found with the six cylinders containing mercury. The pressure was increased more slowly for the higher numbered cylinders ; with the four first the

TABLE I.

No. of Cylinder.	Breaking Pressure Kgm. cm ² .	Rate of Increase of Pressure.	Total Duration.	Location of Crack.	Remarks.
1	10250	1250 kgm. in 30 sec.	3½ min.	-123°	{ Pressure on 1, 3, 5, 7, was increased uniformly { Broke on second trial { Leaked on first at 2750
3	4750	" " "	1½ "	+107°	
5	3250	1250 kgm. in 60 sec.	1½ "	+ 64°	
7	3375	625 kgm. in 60 sec.	4¼ "	+ 11°	
9	4000	1500 for 3½ min. 2750 for 10 min.; breaks at 4000 after ½ min.	14 "	- 25°	{ Pressure on 9 and 11 increased discontinuously
11	3000	At 2750 for 46 min. Breaks at 3000 after 5 min.	51 "	-106°	

pressure was increased uniformly at the rate indicated, while with the two others it was increased in discontinuous steps as shown. In making the tests, pressure was first pushed to 1500 atmos. and kept there for several minutes to make sure that there was no leak and everything was in working order. The time given in the duration column is exclusive of the time occupied by the preliminary application of 1500. It is evident that the data admit of no quantitative comparison as the great discrepancy between tests 1 and 3 made under as nearly as possible the same conditions shows. However, these two tests were made with a high rate of increase of pressure. Those made with a slower rate show much more consistent results. In general it appears that the slower the rate of increase of pressure the lower the bursting pressure, which apparently has as its lower limit about 3000 atmos. The data are not inconsistent with the view that there is a critical pressure which will produce rupture if applied for an infinite time ; pressures above this produce rupture in constantly less times.

The location of the crack is an important consideration. The crack in each cylinder is in an axial plane, extending the entire length of the cylinder. It was located by measuring the angular distance from a fiducial line marked the length of the bar from which the pieces were

cut. The diagram (see Figure 2) showing the location of the crack in the several cylinders makes clear that the rupture does not take place along a flaw in an axial plane extending originally throughout the entire bar. Furthermore, since the manner of fracture of each cylinder demands that the flaw be in an axial plane if the fracture is due to a flaw, and since it seems improbable that a flaw throughout the length of one cylinder should not extend into the neighboring cylinders, the conclusion seems justified that the rupture is not due to a flaw.

Now compare with this the tests for the other set of six cylinders from the same bar. (See Table II.)

The difference between these two sets of tests is sufficiently striking. Not one of the cylinders filled with a fluid other than mercury was broken during the tests, although in several cases the test was terminated by an irrelevant accident. The

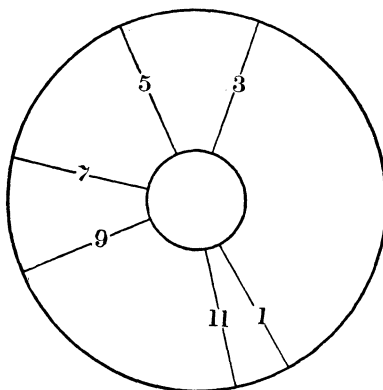


FIGURE 2. Orientation of the crack with respect to the original bar in the six cylinders broken with mercury.

TABLE II.

No. of cylinder.	Maximum Pressure $\frac{\text{Kgm.}}{\text{cm}^2}$.	Manner of applying Pressure.	Remarks.	Fluid.
2	23500	Rate of increase not noted	Packing plug blows out	Glycerine and water
4	19000	From 1500 to 15000 at rate of 1250 in 30 sec. Held at 15000 for $2\frac{1}{2}$ min., 17500 for 3 min.	Packing plug blows out	Glycerine and water
6	15200	From 1500 to 11000 uniformly in $4\frac{1}{2}$ min. Held here for 3 min., then at 13500 for 1 min.	Terminated by leak	Glycerine and water
8	24000	15 min. in reaching max. Held here for 6 min.	Leak after 6 min.	Glycerine and water
10	20250	Held at 16500 for 2 min.; at 20250 for 45 sec.	Plug blows out	Ether
12	24000	1 hour in reaching max. at uniform rate. Held her for 8 min.	No leak	CS ₂

maximum pressure reached by three of the cylinders without breaking was 24000 atmos., over 8 times the lowest breaking pressure of the cylinders filled with mercury, and nearly $2\frac{1}{2}$ times the maximum breaking pressure. Greater pressure than 24000 atmos. was not applied because the limit of the press was reached. Of course the stress produced in a cylinder by internal fluid pressure depends only on the pressure in the fluid and not on the nature of the fluid. It must be, then, that the mercury takes some special part in producing rupture quite apart from the stress produced by it.

The magnitude of the fluid pressures mentioned here requires brief comment, because without a word of explanation it may seem so large as to cast discredit on the accuracy of all the data. In the first place, a steel of the kind described above with the indicated heat treatment is the only steel known to the author that will stand the pressures used. The best grades of carbon tool steels will not stand much more than 18000 atmos. As to the measurement of the pressure, similar apparatus has been used up to 13000 atmos. and the pressure measured directly with an absolute gauge with an accuracy of $\frac{1}{10}$ per cent. Absolute measurements have not been made above this, and it is possible that the friction of the packing may become unexpectedly large, although no evidence of this has been found. However, it makes no difference what the friction above 13000 is; the fact stands incontestable, for the breakage produced by mercury is in a region open to easy direct measurement, while the other cylinders have stood a pressure certainly several-fold greater.

All these results so far were obtained with hardened chrome nickel steel. Search was now made for the same effect in other steels. A cylinder of nickel steel of similar dimensions to the above, but left soft, was tried. This was filled with mercury. Pressure was kept at 8000 for 3 hours, then pushed gradually to 15000, where the increasing non-elastic stretch became so great as to let the mercury past the packing. The behavior here was exactly like that of a similar cylinder filled with water and stretched beyond the elastic limit: the elastic limit in the two cases was the same, as also the manner of yield and the shape into which the cylinder was deformed. Apparently, then, mercury exerts no selective action on the soft nickel steel. A similar cylinder of bessemer steel filled with mercury was left exposed to 3500 atmos. for 14 hours, and subsequently the pressure was increased until the mercury blew past the packing, exactly as for similar cylinders filled with water. It should be noted that non-elastic yield occurs for bessemer steel at pressures much lower than 3500, perhaps as low as 2000 atmos. The explanation finally adopted attaches some significance to the value

of the elastic limit. The two cylinders above were tested at pressures beyond this limit. To test whether a soft cylinder would be broken by a pressure under the elastic limit if the pressure were sufficiently prolonged, a cylinder of soft nickel steel filled with mercury was exposed for three weeks to 4000 atmos. without rupture. At the end of three weeks, pressure was increased and rupture took place at 12000 atmos. The break was remarkable, as the cylinder showed no preliminary stretch as all soft steels do, but snapped like a piece of hardened tool steel. This may have been due to fatigue from the prolonged application of pressure, or it may be that weakening by the action of mercury had started at the lower pressure and that the cylinder would have finally broken at 4000, had the application been sufficiently prolonged.

An attempt was made to make a series similar to that on the nickel steel on cylinders cut from a bar of tool steel containing 1.25 per cent carbon. Several of these cylinders cracked in hardening so that a complete set of observations could not be made. The few successful tests made with the hardened tool steel cylinders, however, confirm the conclusions reached with the hardened nickel steel. Thus one cylinder with no hardening flaw burst at 4000 atmos. when filled with mercury, and a similar cylinder, which had a hardening flaw in it, broke at 6500 on the second application of pressure when filled with water.

Another series of tests was now tried which gave the clue to the final explanation. Pressure was applied to cylinders of the form shown (see Figure 3), in which the end opposite the piston is left solid, and may be of varying thickness. In the first tests this bottom was left only $\frac{1}{8}$ " thick. The cylinders were made of the same nickel steel as above, hardened in oil. One, filled with mercury, ruptured by blowing out of the bottom at a pressure of 2400 atmos. The bottom blew out of a second in which the transmitting fluid was water, at a pressure of 12700 atmos. The manner of rupture was very different in the two cases. When water was used, the bottom was blown out in the form of a clean punching, slightly less in diameter than the hole and slightly bulged as one would expect. (See Figure 4.) On the other hand, the piece blown out by the mercury was in the form of a conical cap twice

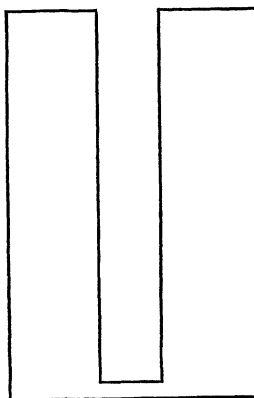


FIGURE 3. Another form of test cylinder for water or mercury, made of hardened nickel steel.

the diameter of the hole, as indicated in Figure 5. The structure of the ruptured metal from A to B was very coarse and granular, remarkably like the structure of brass made rotten by mercury. Between the grains of the steel were minute drops of mercury, and the fractured surface was partially wetted by mercury when plunged beneath a mercury surface. The only clean break was around the edge of the cap (BC), where the rupture took the form of a clean shear as for the piece broken with water.

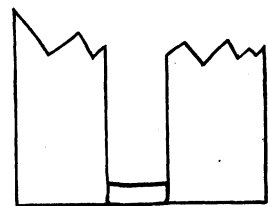


FIGURE 4. Form of the break of the cylinder of Figure 3 when the fluid exerting the pressure is water.

The corresponding tests with tool steel cylinders were hard to carry out because of loss of the cylinders on hardening. However, two successful tests were made.

The bottom of one cylinder, when filled with mercury, blew off at 2700 atmos., while a similar cylinder filled with water did not fail until 5200 atmos. The manner of failure was different from that of the nickel steel, the detached piece being in the form of a frustum of a cone, as shown in Figure 6. The form of this cap was

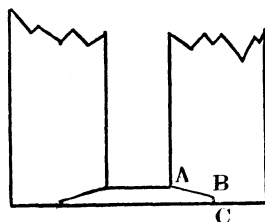


FIGURE 5. Form of the break of the cylinder of Figure 3 when the fluid exerting the pressure is mercury.

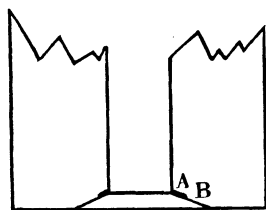


FIGURE 6. Form of the break in a cylinder like that of Figure 3 of hardened tool steel when the fluid exerting the pressure is mercury.

the same for both water and mercury, the only difference being that the one fractured with mercury showed unmistakable amalgamation over a limited region (AB). This, together with the curious fracture of the nickel steel piece, suggested the amalgamation of steel by pressure as a possible explanation.

Experiment was also made on two cylinders of tool steel similar to the above, except that the bottom was $\frac{1}{2}$ " thick instead of $\frac{1}{8}$ ". The cylinder filled with water stretched non-elastically and leaked at a pressure of 8000 atmos., while that filled with mercury failed at 4000 by the blowing out of mercury along a crack. This break was more like that described by Amagat than any other in the course of these experiments, but even here the break was

distinctly visible, while Amagat states that he could find no trace of the crack with a microscope. (See Figure 7.)

In all these tests of the soft steel cylinders the punched out pieces were found more or less amalgamated around the sheared edges. In particular, when the cylinder of soft tool steel last mentioned was cut so that the fissure was exposed, it showed beautiful amalgamation over the entire surface of the rupture. This led to a short investigation of the possibility of amalgamating iron or steel. It has been known for some time that mercury is capable of dissolving a small quantity of iron, and that conversely an iron surface may be amalgamated by mercury.⁴ This amalgamation is a matter of some difficulty, which may be made to take place by certain chemical or electrical reactions, but under ordinary conditions does not occur at all. It does not seem to have been noticed that under proper conditions the amalgamation of iron is a matter of the greatest ease, the

difficulty under ordinary conditions being due apparently to a thin protecting layer of oxide. The following experiment showed strikingly how great the affinity between clean iron and mercury is. A piece of iron was broken underneath a mercury surface so that the freshly ruptured surface came directly in contact with the mercury. The diagram illustrates the form of experiment. (See Figure 8.) The test piece, in the shape of a thin hollow cylinder, is covered with mercury in an iron receptacle, and broken by forcing a wedge into the hole. In every case the broken surface is brightly and completely amalgamated, the mercury wetting it exactly as water wets a surface to which it adheres. The same result was obtained

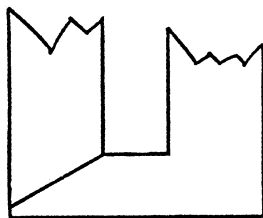


FIGURE 7. Form of the fracture in a cylinder of soft tool steel when the fluid exerting the pressure is mercury.

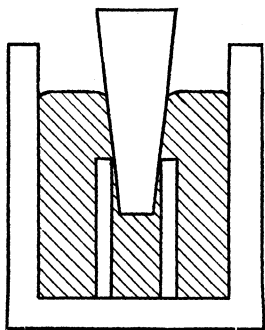


FIGURE 8. Apparatus for fracturing steel under the surface of mercury.

⁴ See, for example, Richards, Wilson, and Garrod-Thomas, *Pub. Carnegie Inst. Wash.*, No. 118, 54, 1909; also Richards and Garrod-Thomas, *ZS. Phys. Chem.*, **72**, 181 (1910).

both in its natural state and quenched from a red heat, and with cast iron.⁵ The same effect is shown by the same grades of steel when broken off by twisting under a mercury surface, showing that the amalgamation does not depend on the nature of the rupturing stress. This effect was shown in a striking way by one of the hardened tool steel cylinders. (See Plate.) This cylinder broke on the first application of pressure at 1500 atmos. Examination showed a small hardening crack at A from which the crack spread into the sound metal. The mercury, escaping under pressure through the freshly opened crack, produced nearly complete amalgamation of the entire section of the cylinder, as the photograph shows.

But on the other hand, all attempts failed to amalgamate the freshly broken surface if it had once come in contact with the air. A test piece like the above was supported directly over a mercury surface so that the fragments fell immediately into the mercury when rupture occurred. No trace of amalgamation was obtained here, as was also no trace with several modified forms of the experiment in which immersion was not so immediate.

Experiments were now made to find whether the amalgamation so produced might be made to work its way through the mass of the metal. Fragments of the above amalgamated test pieces were sealed into a bulb containing mercury so designed that the pieces should be kept below the surface of the mercury. The air was boiled out, the bulb sealed, and the whole kept at a temperature of 180° C. for three hours in an oil bath. The pieces were then examined for amalgamation by breaking them across. The hardened nickel steel piece showed amalgamation throughout its entire mass, the bessemer showed isolated splotches of amalgamation, while none of the others showed any effect. Similar amalgamated bits from the broken test pieces were now submerged in mercury, which was subjected to a pressure of 6500 atmos. at room temperature for six hours. All of the specimens, except the soft tool steel, now showed amalgamation throughout the interior. The hardened nickel steel piece was amalgamated completely, while the amalgamation of the others was not so perfect, being confined to patches near the surface.

Further, pressure by itself is not capable of producing amalgamation

⁵ Aluminum may also be amalgamated by rupturing under the surface of mercury. Aluminum so treated, when exposed to the air, shows the characteristic tree-like growth of the oxide. The same effect is also shown in nickel and cobalt. It should be remarked that the amalgamated iron surface shows no tendency to oxidize in the air, but keeps its silver luster untarnished at least for months.

on a steel surface or in the mass of the metal unless the amalgamation has been started on the surface by some other means. This was shown by subjecting rods of the three kinds of steel (hard and soft nickel steel, hard and soft tool steel, soft and quenched bessemer) to a pressure of about 6500 atmos. for twelve hours or more under mercury. These rods were scoured bright with fine emery paper immediately before being plunged into the mercury. The fracture after pressure treatment showed not the slightest trace of amalgamation. Reference may be made to some earlier experiments in which no gain of weight could be detected in steel pieces subjected to hydrostatic pressure in mercury. The possibility of amalgamation by pressure was also tried in another form. A hollow cylinder of hardened nickel steel was submerged in mercury, and pressure applied to the outside. The only difference between this and the case of the solid rod is that in the former the stress throughout the metal is not uniform, as it is in the latter. It was thought conceivable that mercury might be forced through metal in which the stress was not the same in every direction, while it might show no tendency to work its way through a mass in which the stress was already hydrostatic. The experiment, however, showed no amalgamation in this case either.

This test for amalgamation by examining the nature of the fracture showed itself so easy to apply and so unmistakable in its indications that it was now applied to the examination of the cylinders which had formed the subject of the first tests. The possibility of the amalgamation of the cylinders as an explanation had at first been discarded because the inner wall of the cylinder, where it was to be most expected, showed no indications of any amalgamation and because attempts to detect the presence of mercury throughout the mass of the metal by microscopic analysis of the polished and etched cross section had given no result. Professor Sanveur had been kind enough to examine four test pieces cut from different cylinders, three of which were ruptured with mercury and one with water. He found martensitic structure in the three former pieces, and only a very fine granular structure in the other. There was no visible trace of mercury in the pores, nor anything to suggest amalgamation. The differences of structure might be due merely to the slight differences in heat treatment occasioned by the separate hardening of the cylinders. More careful regulation of the conditions would be necessary to settle this point.

The fracture test was applied by cutting a scarf about $\frac{1}{4}$ " deep all around the cylinder with a thin emery wheel, and then breaking the cylinder at this scarf with a hammer. All the cylinders broken with the mercury showed the same characteristics. (See Figure 9.) The

crack was in a radial plane; surrounding this crack on either side was a band within which the coarser structure and the silver luster showed that the steel had been amalgamated. Besides this band of amalgamation flanking the crack, which was present in every cylinder, there were other irregular splotches of amalgamation growing either from the central hole or from the flanking band. No cases were found of isolated islands of amalgamation in the midst of untouched metal.

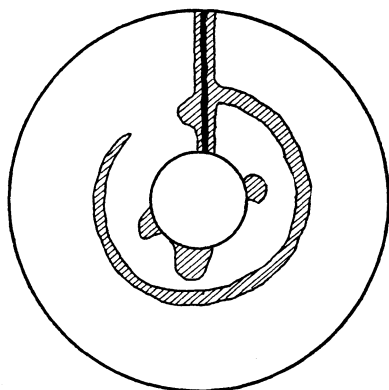


FIGURE 9. The form of the amalgamated region in cylinders like those of Figure 1 when broken with mercury.

The diagram gives an idea of typical forms of this amalgamation, although so many varieties were seldom found in one specimen. In one specimen the amalgamation had grown in the form of a nearly complete ring with no contact with the interior except through the infected region about the crack, in the manner shown in the drawing. The tool steel cylinders showed the same effect, except that the amalgamated band about the crack was not so broad as for the nickel steel, and the other patches of amalgamation were less numerous. The peculiar fracture indicating amalgama-

tion was found in none of the cylinders which were broken in the absence of mercury. Several such cylinders were examined, some of hard or soft tool steel, and some of nickel steel, broken with water after the repeated action of the maximum pressure of 24000 atmos.

Such are the experimental facts which must be explained. It seems evident that the premature breaking of the cylinders filled with mercury was due to the weakening of the steel produced by amalgamation. The fact of amalgamation seems sufficiently proved by the study of the fracture. That amalgamated steel would be weaker than the untouched steel seems obvious enough without the necessity of special experiment to prove it. The fact was proved incidentally several times, however, when parts of the steel packing appliances which had been used with the mercury cylinders were used over again with the cylinders filled with water. The packing plugs in these circumstances always broke at a pressure very much less than the normal breaking pressure and with a fracture showing bright amalgamation. In explanation of the amal-

gamation of these cylinders we have in the first place the strong natural affinity between iron and mercury. This is prevented from coming into play under ordinary circumstances by a thin layer of dirt on the surface. But it seems reasonable to suppose that amalgamation will start in the mass of the metal if the mercury can be once forced into the pores, since under these circumstances the iron and mercury coming into contact with each other would be clean and the natural chemical affinity come into play. The argument consists in showing that in those cases where amalgamation took place the conditions were such as to favor the introduction of mercury into the pores of the steel, even if the surface were not amalgamated. Then after amalgamation is once started in the mass of the metal it is assisted in the rapidity of its growth from the amalgamated region by the action of hydrostatic pressure.

This discussion demands a slight consideration of the nature of the strain in a hollow cylinder exposed to internal fluid pressure. The stresses in the metal of the cylinder consist of a pressure (negative) across planes perpendicular to the radii, and a tension (positive) across radial planes. These stresses are greatest arithmetically at the interior surface, but the algebraic sum is constant throughout the mass of the cylinder. This has as a consequence that the volume strain in the cylinder is a dilation and is everywhere constant, so that the pores are opened up by the action of the stress and the entrance of mercury facilitated. This holds while the strain remains elastic. But when the internal pressure exceeds a certain value so that at the inner surface the algebraic difference between the radial pressure and the circumferential tension exceeds a critical value depending on the elastic limit, the strain becomes inelastic, the tension changes over to a pressure so that both principle stresses become compressions, the volume strain changes from a dilatation to a compression, and the pores close up. So that with a steel of low elastic limit the type of stress may change, giving a volume compression, at a lower value of the fluid pressure and therefore at a smaller preliminary volume dilatation than in a steel of higher elastic limit. This view as to the nature of the stress in a thick cylinder stressed beyond the elastic limit is supported by many other experiments on the bursting of thick cylinders. An account of these experiments will be published in another paper.

The difference found in the rupture points between soft and hardened steel is to be ascribed to two causes. One is the greater intrinsic ease of driving amalgamation through a mass of hardened steel by hydrostatic pressure. This was proved by the experiments on the broken amalgamated test pieces. It may be due in part to chemical difference between the hard and soft steel, but is almost certainly also due in part

to the greater porosity of the hardened steel. It is well known that steel decreases in density on hardening. The other cause is the higher elastic limit of the hardened steel and the consequent wider opening of the pores before non-elastic closing sets in. For facility of comparison the elastic limits of the cylinders of the various grades of steel are given (see Table III), on the usual assumption that the elastic limit is determined by the maximum stretch at the interior. This assumption is probably not very near the truth, so the results can be expected to show only qualitative agreement. This table does not apply to the

TABLE III.

Kind of Steel.	Assumed Elastic Limit in Tension lbs. in ² .	Internal Pressure required to reach Elastic Limit. Atmos.	Minimum Bursting Pressure with Mercury. Atmos.
Bessemer . . .	40000	2000	Same as with water
Soft tool steel .	75000	4000	Same as with water
Hard tool steel .	150000	8000	4000
Soft nickel steel	90000	4800	Same as with water
Hard nickel steel	225000	12000	3000

cylinders in which the bottoms were blown out, as here the stress is of a different nature and the above values of the elastic limit do not hold. It appears from the table that only those cylinders were broken in which the stress was below the elastic limit. That the cylinders of bessemer and soft nickel steel were not broken may be explained by supposing that the pressure required to open the pores wide enough to force the mercury in is higher than the elastic limit.

It remains to explain the form of the amalgamated region found in the hardened nickel steel cylinders; i. e., bands on either side of the crack. It seems certain that slight inequalities in the structure of the steel will greatly affect the ease of amalgamation. This seems proved by the splotches of amalgamation found throughout the broken test pieces amalgamated by hydrostatic pressure and throughout the broken cylinders. Conceive, then, of a hollow cylinder filled with mercury subjected to pressure. The pressure expands the pores of the metal, and in consequence of the high mobility of the mercury molecule the mercury is forced into these pores through the layer of dirt lining the hole. At certain places where the metal is more susceptible the

amalgamation spreads more rapidly than it does at others. But now the metal is weakened at each of these infected places, and the type of strain is modified as it would be by the presence of a flaw. The strain will be redistributed, the brunt of the strain coming at the point farthest removed from the center, where consequently the pores of metal will be still further distended. That is, at this point the amalgamation will proceed most rapidly. It is evident that the continuation of this process will produce a band of amalgamation travelling out along the radius. When the amalgamation reaches the outside, or approaches sufficiently close, the metal gives way, the crack appearing through the midst of the weakest region, that is, through the center of the amalgamated band. It is evident that when the process of amalgamation has once started in this way, it will proceed more and more rapidly as the resisting thickness of sound metal becomes less, thus accounting for the smallness of the other amalgamated regions. One cylinder was found, however, in which an amalgamated patch had worked its way nearly half way to the outside diametrically opposite the crack.

Failure to produce amalgamation in the rods subjected to hydrostatic pressure is to be explained by the fact that neither can the amalgamation begin at the surface, because of the thin layer of dirt, nor can the mercury force its way into the steel to begin amalgamation there because the interstices in the metal are closed up by the hydrostatic pressure. The same argument of course applies still more to the hollow cylinder submerged in mercury and subjected to pressure on the outside.

The experiments with the cylinders in which the bottoms were blown off are to be explained in the same way. The amalgamation grows most rapidly in the direction in which the distension is greatest, which in this case is diagonally from the corner of the hole. As the amalgamation proceeds it carries the hydrostatic pressure with it. When the region over which this pressure acts has extended so far that the sound metal left can no longer support the stress, it gives way as usual by a clean shear. The fact that mercury was forced through the bottom of a cylinder of soft tool steel (Figure 7), while soft tool steel cylinders of the form of Figure 1 were unbroken by the action of pressure, is probably to be explained by the different strain types in the two cases. In the case of Figure 7 distension in a direction diagonally from the corner of the hole is great enough to allow amalgamation before the pores are closed up by viscous yield. The point has not been worked out in greater detail, however. The disconcerting experiments in which a clean punching was blown out of the bottom of

a soft cylinder with the sides of the punching amalgamated, are to be explained by the fact previously noted that a freshly fractured surface is amalgamated by mere contact with mercury. Breaking across of the punchings showed no evidence of amalgamation in the mass of the punching, so that all the amalgamation must have taken place after rupture. A similar experiment on the hardened nickel steel punching mentioned above showed more or less complete honeycombing of the metal with mercury.

This is as far as the explanation has been carried. Enough has been done to show that there is here a genuine effect, so that pressure can not be transmitted directly by mercury in hardened steel cylinders, and that the effect is due to amalgamation. One-sided pressure is necessary to start this amalgamation, so that when steel is entirely surrounded by mercury there is no danger of amalgamation or of penetration of the mercury into the pores. This fact was made use of in modifying the design of the apparatus spoken of in the first part of the paper.

SUMMARY.

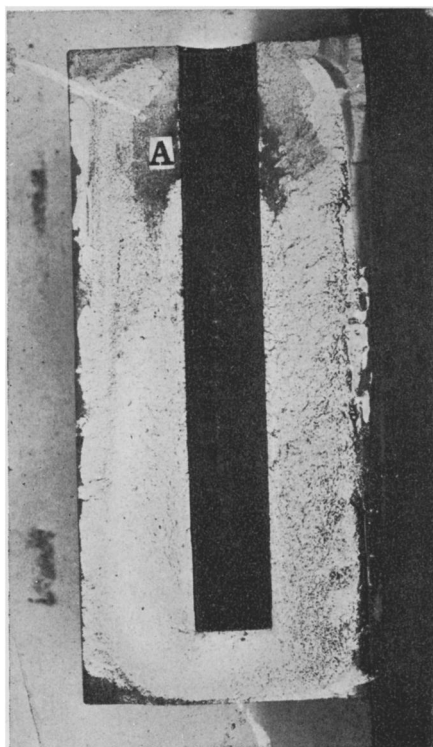
The fact has been established that cylinders of hardened steel will burst at very much lower than the natural bursting pressure when the fluid exerting the pressure is mercury. Soft steel cylinders show the effect hardly at all, the yield point being reached before the pressure can be raised high enough to produce the effect. The fact that this rupture is due to the amalgamation of the steel is established by the examination of the fracture of such cylinders. The unexpectedly great affinity between steel and mercury was established by the complete amalgamation of surfaces broken under mercury, and the enormous effect of the slightest contact with the air was shown. When this amalgamation is once started, the rapidity with which it spreads through the metal is greatly increased by the action of hydrostatic pressure. The spread of mercury through the mass of the steel and the subsequent destruction of the hollow cylinders is produced by two causes, both of which must act together. One is the natural chemical affinity between mercury and steel, shown by the ready amalgamation of freshly broken surfaces. But the amalgamation is never started by the action of pressure alone. In all those cases in which we have had amalgamation, we have had in addition to the chemical affinity a strain of such a nature as to distend the pores of the metal. This allows the entrance of mercury into the pores so that amalgamation may begin, and also facilitates its further growth, which is most rapid in the

direction in which the pores are most distended. It was shown in detail that in all cases in which rupture occurs the strain is of such a type as to distend the metal, and that on the other hand in all those cases in which amalgamation is not produced by pressure, the strain is such as to compress the metal, closing up the pores.

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